1.5 Pinpointing Time

Figure C1.37: Geologists in the late nineteenth century generally agreed that Earth was millions of years old, but there were no accurate methods to measure the absolute age of Earth.

A Question of Time

As the nineteenth century was drawing to a close, the assembled geological record had been built upon accepted principles of relative dating. The increased acceptance of the theory of uniformitarianism had opened peoples' eyes to the concept of deep time. Most geologists accepted that Earth was at least millions of years old. Still, the problem remained: How deep was deep time? There were no reliable methods to measure the absolute age of rocks or Earth itself. Many attempts were made, but different methods gave different results. It would take the development of a new understanding in the area of physics and the invention of new technology to finally understand the extent of time.

Mysterious Rays

radioactivity: the emission of energy from the nuclei of unstable atoms as they change to become more stable atoms

During the late nineteenth century and the early twentieth century, it was discovered that isotopes of certain elements emitted rays invisible to the eye. Marie Curie named this property **radioactivity**. The discovery of radioactivity attracted the interest of a bright young physicist named Ernest Rutherford. While working at Montreal's McGill University, Rutherford discovered that the energy emitted from radioactive materials was in the form of high-speed particles. He was also able to measure the intensity of this radiation by detecting the number of particles emitted per second.

Figure C1.38: Marie Curie used simple technology to study radioactivity.

An Atomic Clock

While measuring the radioactive intensity of a sample of gas containing radon-220, Rutherford discovered a remarkable property of radioactive materials: the intensity decreased (or decayed) over time. Every 55.6 s, the radioactivity of the thorium decreased by half. If its original intensity were 100%, the intensity 55.6 s later was only 50% of the original value. If another 55.6 s passed, the intensity was again cut in half to be only 25% of the original value. Rutherford called the decreasing intensity **radioactive decay**.

No matter what size of gas sample Rutherford started out with, the radioactive intensity was cut in half every 55.6 s. This constant time increment is now called a **half-life**. It occurred to Rutherford that half-lives were like minutes ticking by on a clock. He had discovered the first use of atoms to estimate time.

- radioactive decay: the disintegration of an unstable atom, which results in the release of energy in the form of radiation
- half-life: the time taken for half of a radioactive sample to decay

A half-life is a constant increment of time that depends on the particular isotope.

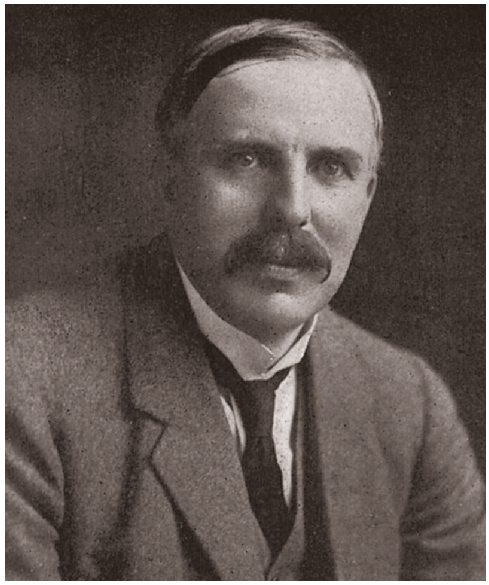


Figure C1.39: Ernest Rutherford discovered that energy was discharged from radioactive materials through high-speed particles.

DID YOU KNOW?

Rutherford measured the speed of alpha particles released by radioactive decay at 24 000 km/s! He showed that this kinetic energy could be transformed into heat. Now scientists believe that radioactive decay in Earth's core is the ongoing source of heat that drives convection currents in the mantle.

Investigation

Constructing a Decay Curve

Problem

What is the shape of a radioactive decay curve?

Science Skills

- ✓ Performing and Recording
- ✓ Analyzing and Interpreting

Part A: Using Arts and Crafts

You will use paper strips to represent the radioactive sample.

Materials

- coloured paper
- scissors
- glue
- copy of the radioactive decay blank bar graph (available on the Science 20 Textbook CD)

Procedure

step 1: Cut out two strips of coloured paper about 1 cm thick. These strips should be the same height as the vertical axis on the vertical scale provided in the handout.

step 2: Paste one of the strips onto the handout as shown in Figure C1.40.

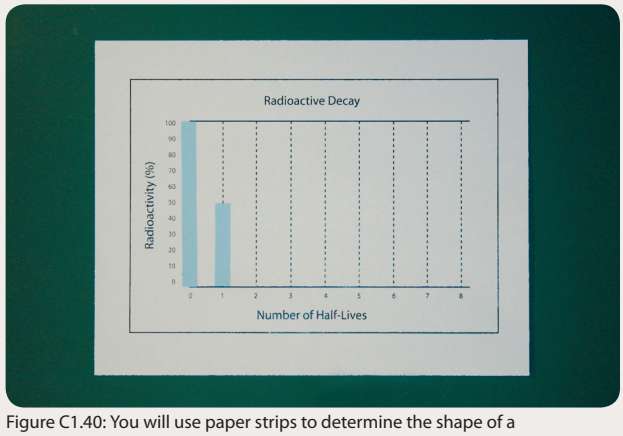


Figure C1.40: You will use paper strips to determine the shape of a radioactive decay curve.

step 3: Fold the second strip so that it is half as long as the first one. Cut the second strip at the crease.

step 4: Paste one of the halves as shown in Figure C1.40.

step 5: Continue this process of cutting and pasting until the paper has gone through eight half-lives.

step 6: Draw a dot at the very top of each strip, and then draw a smooth curve through the dots.

Analysis

1. Describe the curve's shape.

2. Determine if the radioactivity will ever reach 0%. Explain.
3. How many half-lives have passed for a strip that's emitting 60% of its original intensity?

Part B: Using Math

Materials

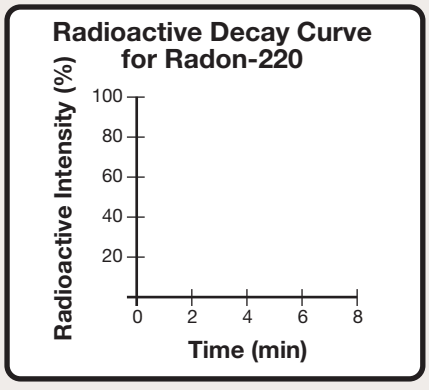
- graph paper or a spreadsheet program

Procedure

step 1: Copy and complete the data table.

Time (min)	Radioactivity (%)
0	100
1	50
2	25
3	
4	
5	
6	
7	
8	

step 2: Use graph paper or a spreadsheet program to construct a radioactive decay curve for radon-22. For simplicity, say the half-life is about one minute (even though it's really 55.6 s). This sample graph shows you how to set it up.



Interpretation Questions

4. Compare the shape of your graph from Part B with your graph from Part A.
5. Define half-life.
6. Compare the half-life effect of radioactive decay with the workings of a clock.

The New Alchemy

Why did radon-220 atoms decay? This question led Rutherford to the strangest part of all—he found that the radon-220 was unstable. It spontaneously changed into polonium, a more stable element. As the radon-220 changed, it released energy in the form of radiation. This reminded Rutherford of the alchemists, early chemists who dreamt of changing inexpensive elements like lead into rare, expensive elements like gold.

Rutherford did not discover a way to make gold from other atoms, but he did discover that elements could naturally change their identities. When discussing radioactive decay, two **isotopes** are often referred to: the original unstable atom called the *parent isotope* and the more stable product termed the *daughter isotope*.

isotope: a particular variety of an element as defined by its atomic mass

Radioactive Dating of Rocks and Fossils

Rutherford, Curie, and others found that no matter how much heat, cold, or pressure they applied to radioactive samples, the shape of the decay curve and the length of the half-life were the same. All of the radioactive elements decayed like clockwork; the half-life always elapsed as constant intervals of time. Because the radioactive decay of an element occurs at a fixed rate—a half-life—the decay process can be used to measure the time passed since a rock or fossil has formed.

Counting Atoms Is Hard

After discovering the properties of radioactive decay, Rutherford realized almost immediately that the pattern of radioactive decay could be used to determine the age of rocks and even Earth itself. He attempted to apply this thinking but was never successful because of the limited technology available to him.

Since then, scientists have developed very precise methods of counting the number of each type of atom in a sample to identify the amount of parent isotopes and daughter isotopes present.

The greatest breakthrough occurred with the invention of the mass spectrometer just after World War I. This machine can detect the elements (and their isotopes) present in a sample of rock. It can also be used to determine the percentage of each isotope present in the sample, which is an essential step in radioactive dating.

Using Uranium to Date Canada's Oldest Rocks

Some of the world's oldest rocks are tiny crystals called zircons. These are found embedded in other rocks. Some of the world's oldest zircons are found in Canada's Acasta Gneiss Rock Formation in the Northwest Territories. Zircons contain uranium and are amazingly durable. The rock around the zircons can even be melted and the zircons will remain unchanged. This makes zircons great for radiometric dating. The uranium clock is set at zero when the zircon forms—the uranium begins to decay from that point forward. Uranium can also be used to date volcanic ash layers. By knowing the age of a volcanic ash layer in a stratigraphic sequence, scientists can estimate the age of layers above and below the volcanic ash that can't be dated directly.

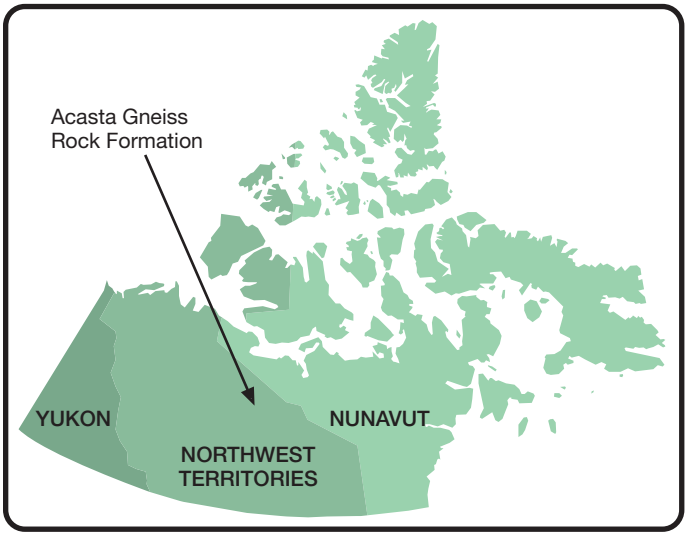


Figure C1.41: The Acasta Gneiss is located in the Northwest Territories.

4 billion years ago:
Canada's oldest rocks form

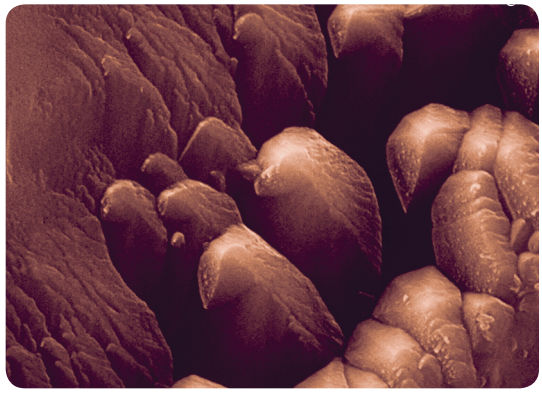


Figure C1.42: The Acasta Gneiss in the Northwest Territories contains Canada's oldest rocks.

Example Problem

A geologist determines the percentages of uranium-238 and lead-206 found in a zircon. She finds that 30% percent of the sample is lead-206. Determine the age of the zircon.

Solution

step 1: Turn to page 557 and find the table of "Elements for Radioactive Dating" and the "Radioactive Decay Curve." A handout of a large, user-friendly decay curve is available to be printed out from the Science 20 Textbook CD.

step 2: Determine the parent and daughter nuclides by using the "Elements for Radioactive Dating" table.

parent: uranium-238

daughter: lead-206

step 3: If necessary, determine the percentage of parent nuclide remaining in the sample. Use the fact that the percentages of the parent and daughter nuclides must add up to 100%. In this case, it is necessary because the daughter percentage is given, rather than the parent percentage.

(100% total) - (30% daughter) = 70% parent

step 4: Use the decay curve to determine the number of half-lives that have elapsed. About 0.50 half-lives have elapsed.

step 5: Look up the amount of time for each half-life for that element. Multiply it by the number of half-lives.

$$\textbf{(0.5 half-lives) (4.47 } \times \textbf{ } 10^{9} \textbf{ a/half-lives) = 2.235 } \times \textbf{ } 10^{9} \textbf{ a.}$$

The abbreviation for annum is *a*, which means year. Use the same number of significant digits in your answer as are used in the "Elements for Radioactive Dating" table. The zircon is 2.24 billion years old.

Practice

21. A sample of orthoclase is dated using potassium-40. A mass spectrometer analysis shows that 20% of the potassium-40 is present in the sample. Use this data to determine the age of the orthoclase sample.
22. It's hard to measure the age of Earth because most of the earliest rocks have since been reworked by the rock cycle. The Moon, on the other hand, doesn't have a rock cycle, so its rocks have remained virtually unchanged. Evidence suggests that the material that makes up the Moon was blasted off before Earth had fully formed. This is why geologists suspect that Earth and the Moon are about the same age. During the 1970s, missions to the Moon collected lunar rocks to bring back to Earth for analysis. One of the experiments completed on the collected lunar rocks was determining their age by using radiometric dating. The oldest Moon rock ever dated contains 6% of the daughter nuclide strontium-87. Using this information, determine the minimum age of Earth.
23. Volcanic ash deposits can be dated using uranium. This helps provide a time benchmark for layers above and below. About 100 million years ago, a series of volcanic eruptions blanketed Alberta with ash, which now forms layers known as the Crowsnest Volcanics in Alberta's geological record. Work your way backward to determine the percentage of uranium-235 present in the Crowsnest Volcanics.

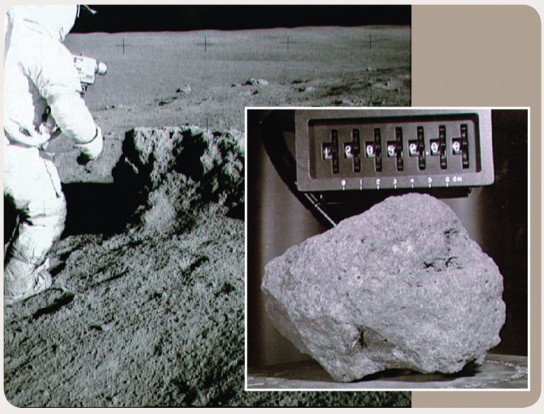


Figure C1.43: Moon rocks are virtually unchanged.

Dating Organic Remains

Carbon-14 is a rare and exotic isotope of carbon that starts out as regular, non-radioactive nitrogen-14. In the atmosphere, carbon-12 combines with two oxygen molecules called carbon-12 dioxide, also known as carbon dioxide. While in the atmosphere, a tiny percentage of the nitrogen-14 atoms are struck by cosmic rays. This turns them into carbon-14. Both types of carbon dioxide are incorporated into plant molecules by photosynthesis. The carbon then makes its way into the food chain.

When an animal dies, the carbon-14 clock is set at zero because dead animals don't ingest carbon. If the animal's organic remains are preserved, the date can be determined by measuring the amount of carbon-14 remaining. Note Figure C1.44. Carbon-14 undergoes radioactive decay to become nitrogen-14, which often escapes from the fossil in gas form. Because the daughter nuclide has escaped, scientists can't directly determine the amount of original carbon-14 in the organism at the time of death. Scientists have to assume that carbon-14 formed in the atmosphere has always been incorporated into organisms at the same rate.

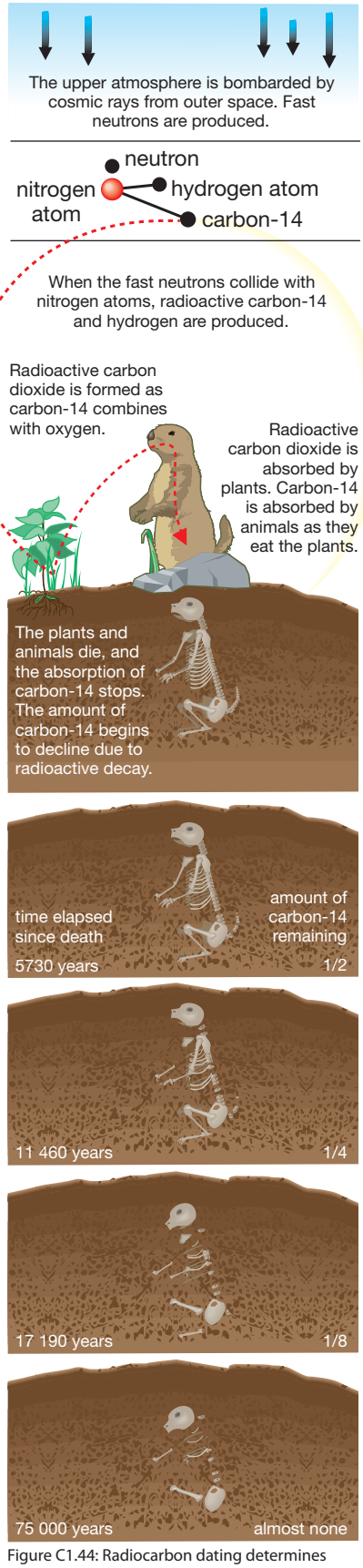

The upper atmosphere is bombarded by cosmic rays from outer space. Fast neutrons are produced.
neutron
nitrogen atom
hydrogen atom
carbon-14
When the fast neutrons collide with nitrogen atoms, radioactive carbon-14 and hydrogen are produced.
Radioactive carbon dioxide is formed as carbon-14 combines with oxygen.
Radioactive carbon dioxide is absorbed by plants. Carbon-14 is absorbed by animals as they eat the plants.
The plants and animals die, and the absorption of carbon-14 stops. The amount of carbon-14 begins to decline due to radioactive decay.
time elapsed since death
amount of carbon-14 remaining
5730 years
1/2
11 460 years
1/4
17 190 years
1/8
75 000 years
almost none

Figure C1.44: Radiocarbon dating determines the age of a fossil.

Practice

24. In the fall of 1991, two hikers discovered a male human body melting in the glacial ice of the Italian Alps. It wasn't until forensic experts were called in that it was discovered the uniqueness of the find. The frozen body of the hunter was much older than anyone guessed. Carbon-14 dating methods found that the body contained 52.5% of the original carbon-14 that would have been in his body at his time of death. Determine the age of the ice mummy.

© South Tyrol Museum of Archaeology/www.iceman.it

Figure C1.45: The age of this ice mummy can be determined by carbon-14 dating.

25. Carbon-14 dating cannot be used to date samples more than 45 000 years old. Provide a possible explanation for this.

1.5 Summary

By using radioactive decay, modern geologists now have the ability to determine the absolute age of rocks and the remains of dead organisms. After Curie and Rutherford discovered the fundamental properties of radioactive decay, technology—such as the mass spectrometer—enabled the analysis of isotopes. This led to more accurate predictions of age. With the advent of radioactive dating, numbers were finally added to the Geological Time Scale. Dates can now be assigned to rock layers that contain radioisotopes.

1.5 Questions

Knowledge

1. Identify a major problem facing geologists at the end of the nineteenth century.
2. Describe the oldest rocks in Canada. Where are they?
3. Why does radioactivity make a good clock?
4. Describe what radiometric method is used to date organic remains.

Applying Concepts

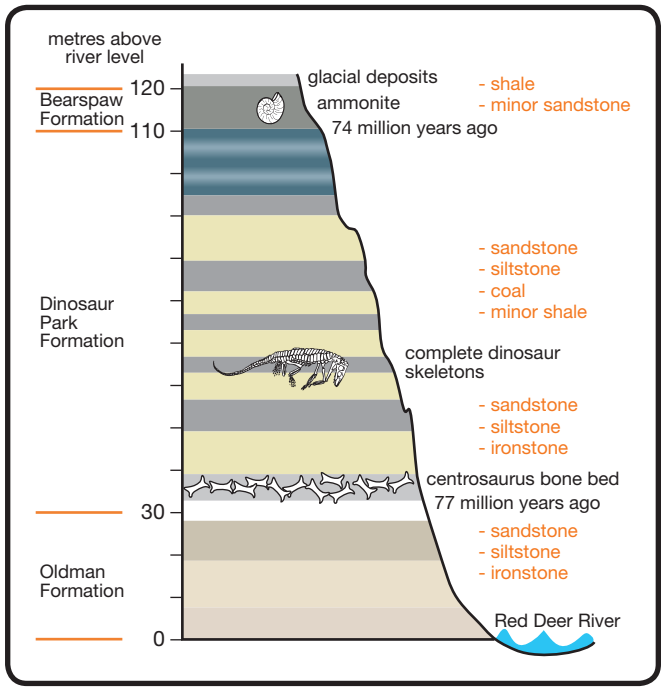


Figure C1.46: An outcropping of the Red Deer River outlines soil composition.

5. Figure C1.46 shows an outcropping of the Red Deer River at Dinosaur Provincial Park near Brooks.
   a. Determine the relative age of the dinosaur skeleton shown in the diagram.
   b. Determine the relative age of the ammonite fossil.
   c. Is the relative age more precise in question 5.a. or question 5.b.? Why?
6. Design a time line showing the development of geological thought and technologies in the study of geology from the time period of Nicolas Steno to the discovery of radiometric dating. Highlight how scientific knowledge is subject to change and how new technologies aid scientific discoveries. Trace a brief description of each item you add to the time line. Be creative. Make a poster or a PowerPoint® presentation, or use an idea of your own.

Chapter 1 Summary

In this chapter you studied the dynamic nature of Earth's internal structure. You examined how early life transformed Earth's atmosphere. You learned that fossils provide information about once-living organisms and that the use of index fossils can be combined with the law of superposition to establish a geological time scale. You learned how theories of geological processes change as new evidence comes to light. This new evidence is often due to technological advances. You have also learned that scientists now have the ability to determine absolute ages of rocks and fossils by using their knowledge of the clock-like process of radioactive decay.

Chapter 2 will continue the story of the changing Earth by using examples from Alberta. You will learn that Alberta is home to one of the rarest and most precious fossil beds in the world and that Alberta's geological circumstances have placed it in a prosperous position when it comes to fossil-fuel reserves. You will also learn how geology and technology are used to discover fossil-fuel resources.

Summarize Your Learning

In Chapter 1 you learned a number of new terms, concepts, and techniques for problem solving. It will be much easier for you to recall and apply the information you have learned if you organize it into patterns.

Since the patterns have to be meaningful to you, there are some options about how you can create this summary. Each of the following options is described in "Summarize Your Learning Activities" on pages 552 and 553. Choose one of these options to create a summary of the key concepts and important terms in Chapter 1.

Option 1: Draw a concept map or a web diagram.	Option 2: Create a point-form summary.	Option 3: Write a story using key terms and concepts.	Option 4: Create a colourful poster.	Option 5: Build a model.	Option 6: Write a script for a skit (a mock news report).

Chapter 1 Review Questions

Knowledge

1. Explain how the stromatolites, which are Alberta's oldest fossils, had an affect on Earth's early atmosphere.
2. Describe the theory of deep time.
3. List the four eras of geological time.

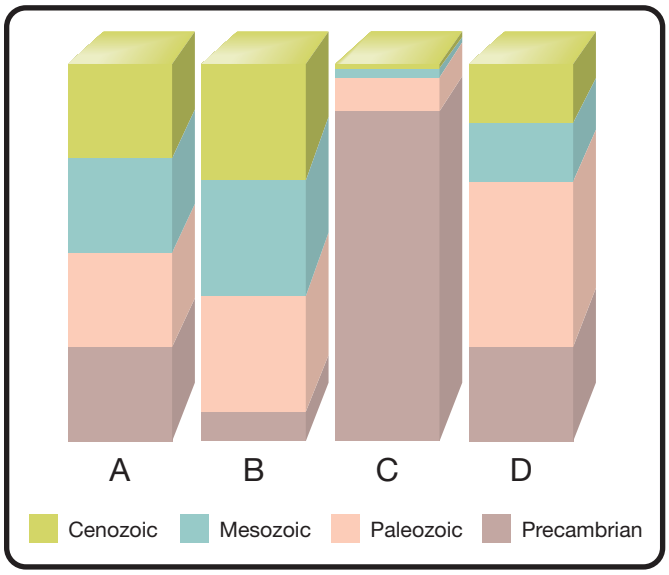


Figure C1.47: These diagrams show different representations of time.

4. Analyze which of the diagrams in Figure C1.47 is the most accurate representation of time for the combined four eras.
5. Describe Alberta's oldest rock outcropping.
6. Zones of rock within Earth's mantle behave as a plastic. Explain this statement.
7. Sketch a diagram showing the layers within Earth. Label each layer.
8. Explain what causes the push and pull on crustal plates.
9. Identify some of the evidence that indicates the Rocky Mountains were once the coastline of Alberta.
10. Describe the hostile environmental conditions that Earth's first organisms had to endure.
11. Scientists suspect that single-celled organisms called cyanobacteria were largely responsible for creating Earth's oxygen-rich atmosphere. Explain how such tiny life forms could produce so much oxygen.
12. Describe evidence suggesting that levels of atmospheric oxygen fluctuated during the Precambrian Era.
13. Describe the organisms living along Alberta's coastal reef at the end of the Precambrian Era.
14. Briefly explain how fossils form and how they can end up high above sea level.
15. State the law of superposition.
16. Explain the difference between relative age and absolute age. Include the major methods used to determine each age.
17. Define the term *index fossil*.
18. Identify three qualities of an ideal index fossil.
19. Describe how the use of index fossils was an integral part of assembling the Geological Time Scale.
20. From general to specific, list the three types of divisions that make up the Geological Time Scale.
21. Describe the theory of uniformitarianism.
22. Identify the three major types of rock.
23. Sketch a simplified version of the rock cycle. Include the processes that create the different rock types.
24. Explain how the existence of a rock cycle provides support for the theory of deep time.
25. Explain why a body of intrusive, igneous rock must be younger than the surrounding rock.
26. Define the term *unconformity*.
27. Describe the process of radioactive decay.
28. Sketch a radioactive decay curve. Include the percentage of parent material remaining and the half-lives.
29. Explain how radioactive decay makes a good clock for measuring the absolute age of ancient objects.
30. Explain how radioactive decay is believed to be the driving force for the rock cycle.
31. Describe how the absolute ages of Canada's oldest rocks were determined.
32. How are the absolute ages of organic remains determined?

Applying Concepts

Use Figure C1.48 to answer question 33.

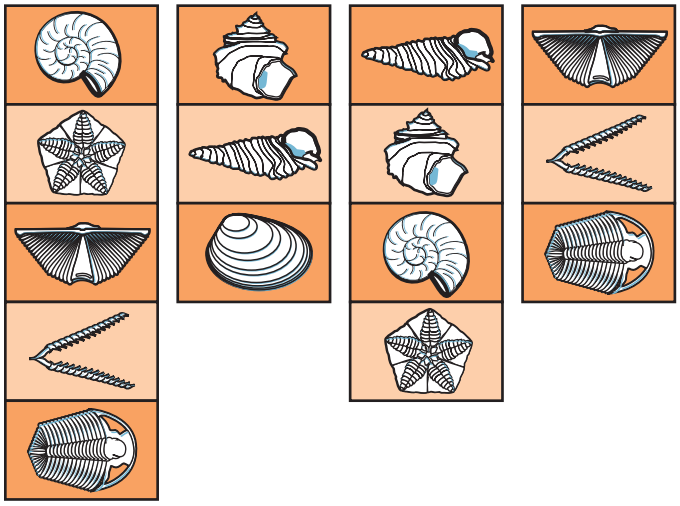


Figure C1.48: Stratigraphic sequences are represented.

33. Figure C1.48 shows four stratigraphic sequences of fossils found at four different locations.

- **a.** Explain how these sequences can be combined to build a larger stratigraphic sequence.
- **b.** Sketch the combined stratigraphic sequence.
- **c.** Label the oldest layer and the youngest layer.

Use Figure C1.49 to answer question 34.

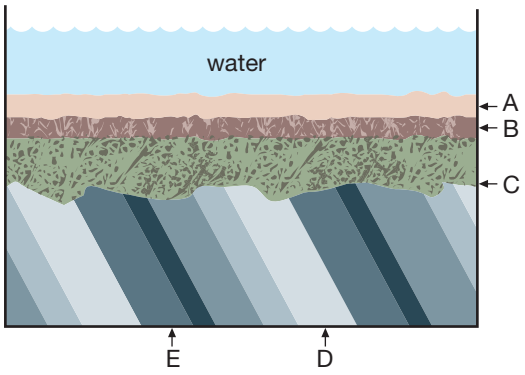


Figure C1.49: A rock cross section is highlighted.

34. Figure C1.49 shows a rock cross section.

- **a.** List rock layers A, B, D, and E in order of age from oldest to youngest.
- **b.** Explain how the identified layers became tilted.
- **c.** Explain what event has occurred at C. Define what this is called.

Use Figure C1.50 to answer question 35.

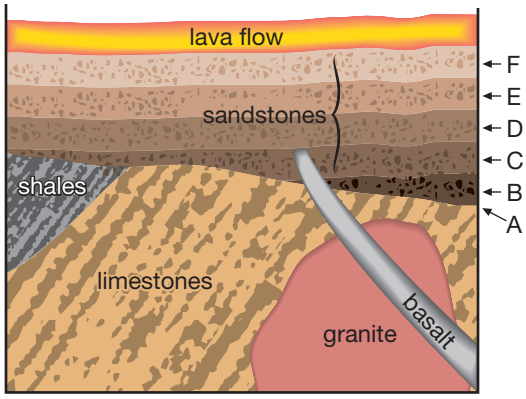


Figure C1.50: This cross section has granite and basalt intrusions.

35. Figure C1.50 shows the cross section of a rock.

- **a.** What types of rock are the granite, basalt, and lava flow?
- **b.** Identify which is older—the granite or the basalt.
- **c.** Identify which is older—the shales or the limestones.
- **d.** Relate what has occurred at A.
- **e.** Identify which group is older—the sandstones or the lava flow.
- **f.** Which layers of sandstone are older than the basalt?

Use Figure C1.51 to answer question 36.

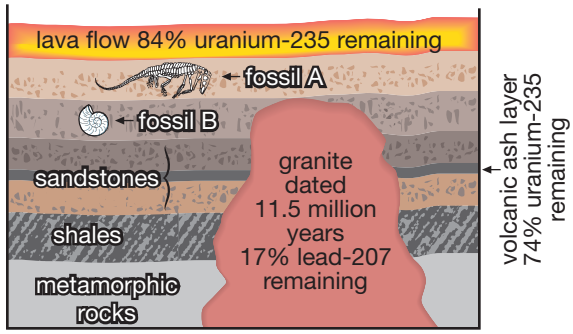


Figure C1.51: Fossils are included in this cross section.

36. Figure C1.51 shows a rock cross section. Determine the ages of

- **a.** the lava flow (Use radiometric dating and the half-life of U-235.)
- **b.** the granite intrusion (Use radiometric dating and the half-life of U-235.)
- **c.** the volcanic ash layer (Use radiometric dating and the half-life of U-235.)
- **d.** fossil A (An exact age cannot be determined. Give a range of ages.)
- **e.** fossil B (An exact age cannot be determined. Give a range of ages.)